Large-Eddy Simulations of Mixing due to Solitary Waves, with Application to the CMO Experiment

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LONG-TERM GOALS

My long-term goal is to develop a facility for the efficient numerical modeling of waves and turbulence in the coastal oceans. The ultimate result will be improved methods for the parameterization of small-scale, coastal mixing processes (particularly sediment resuspension) in mesoscale models.

OBJECTIVES

During the Coastal Mixing and Optics (CMO) experiment, intensive measurements of internal waves and mixing events were obtained at a location on the continental shelf south of Martha's Vineyard. Intense mixing was observed, due both to the effects of local surface forcing and to the effects of remotely-generated nonlinear internal waves. The passage of Hurricane Edouard in September of 1996 caused dramatic changes in the vertical structure of the water column. Not only did the hurricane mix the ocean directly, it changed the nature of ongoing mixing processes that depend on background stratification, such as tide-generated solitons.

Figure 1a shows a nonlinear wave of depression, observed before the passage of Hurricane Edouard, when stable stratification was confined to the upper 25m. After the hurricane passed (figure 1b), the near-surface zone was well mixed, and stratification was confined near the bottom. In that instance, waves of elevation were observed. Similar waves have been observed on the California shelf by Bogucki & Garrett (1997) and found to be very effective at mixing and sediment resuspension. As a result, it is likely that the change in mixing physics brought on by the hurricane persisted long after the event itself had passed.

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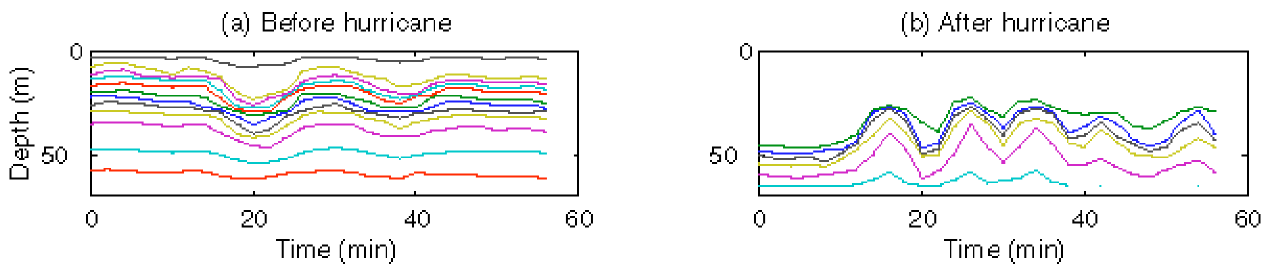

Figure 1: Isotherms separated by 1C, showing internal wave geometry before (a) and after (b) Hurricane Edouard. Data is courtesy of M. Levine and T. Boyd.

This report describes a program of small-scale numerical modeling designed to clarify the mixing properties of solitary waves in a coastal environment, with particular reference to the change in water column dynamics brought on by the hurricane.

APPROACH

In previous research, I have developed a code for the direct numerical simulation (DNS) of turbulent patches in the thermocline. The plan is to modify this model in order to carry out large-eddy simulations of coastal solitons. As an intermediate step, I am carrying out DNS of solitary waves on a smaller scale, such as might be generated in a laboratory experiment.

The first challenge is to initialize the model so as to produce a realistic solitoary wave. It is not possible to include the generation process in the model; instead the model is initialized with a solitary wave solution of the Korteweg-deVries (KdV) equation, modified to include a bottom boundary layer. This waveform differs from observed coastal solitons in several important respects. First, it is an asymptotic solution of the Navier-Stokes equations which assumes inviscid flow and a small-amplitude, long-wavelength disturbance. Nevertheless, this modified KdV soliton is the best available model for the observed solitary waves.

The next step is to include a representation of sediment resuspension. Sediment will be modeled as a continuous concentration field, with weak diffusivity and a realistic settling velocity. Sediment will be introduced into the flow via a bottom flux proportional to the friction velocity. Next, the dissipation terms will be converted to a subgrid model in order to perform LES. The structure function formulation appears to be the most promising candidate (e.g. Skyllingstad et al. 1999), though other models will be tested. Particular attention will be paid to the treatment of the bottom boundary layer, in order to ensure accurate representation of resuspension physics.

At this point, the model will be ready to perform full-scale simulations of coastal solitons. My plan is to simulated two cases: one in which the stratification is restricted to the upper half of the water column, and one in which only the lower half is stratified. These correspond to conditions occuring before and after the passage of Hurricane Edouard, as shown inf figure 1. Note that the wavetrain shown in figure 1b has the form of an undular bore. This corresponds to a “young” waveform, which will later evolve into a sequence of well-separated solitary waves similar to those shown in figure 1a. To facilitate efficient numerical simulation, I will focus on the “mature” solitary wave phase. The results are likely to be valid for younger wavetrains as well, except perhaps in the earliest phase of wave formation in which nearby crests are interacting strongly.

WORK COMPLETED

The initialization procedure has now been implemented, and the inclusion of sediment transport is underway. Preliminary DNS runs are being conducted to test the accuracy of both of these procedures.

RESULTS

Figure 2 shows results from a sample simulation of the post-hurricane case, i.e. that in which the lower part of the water column is stratified. As I hoped, the KdV initialization produces a stable solitary wave with propagation characteristics similar to those observed in both laboratory and observational studies. The simulated flow did not develop motions in the cross-stream direction, so we show only a two-dimensional cross-section.

At this low Reynolds number, the flow is laminar, and mixing processes are correspondingly weak. The most important aspect of this flow for sediment resuspension is the bottom stress. The model was initialized with a weak viscous boundary layer at the bottom which has been intensified over time by the wave-induced flow. The stress increases correspondingly, so that the flow develops strong potential for scouring sediments from the bottom. In the present flow, however, vertical transport of sediments is very weak due to the absence of turbulent mixing. I anticipate that the LES simulations to follow will deliver the enhanced mixing and consequent resuspension seen in the CMO observations.

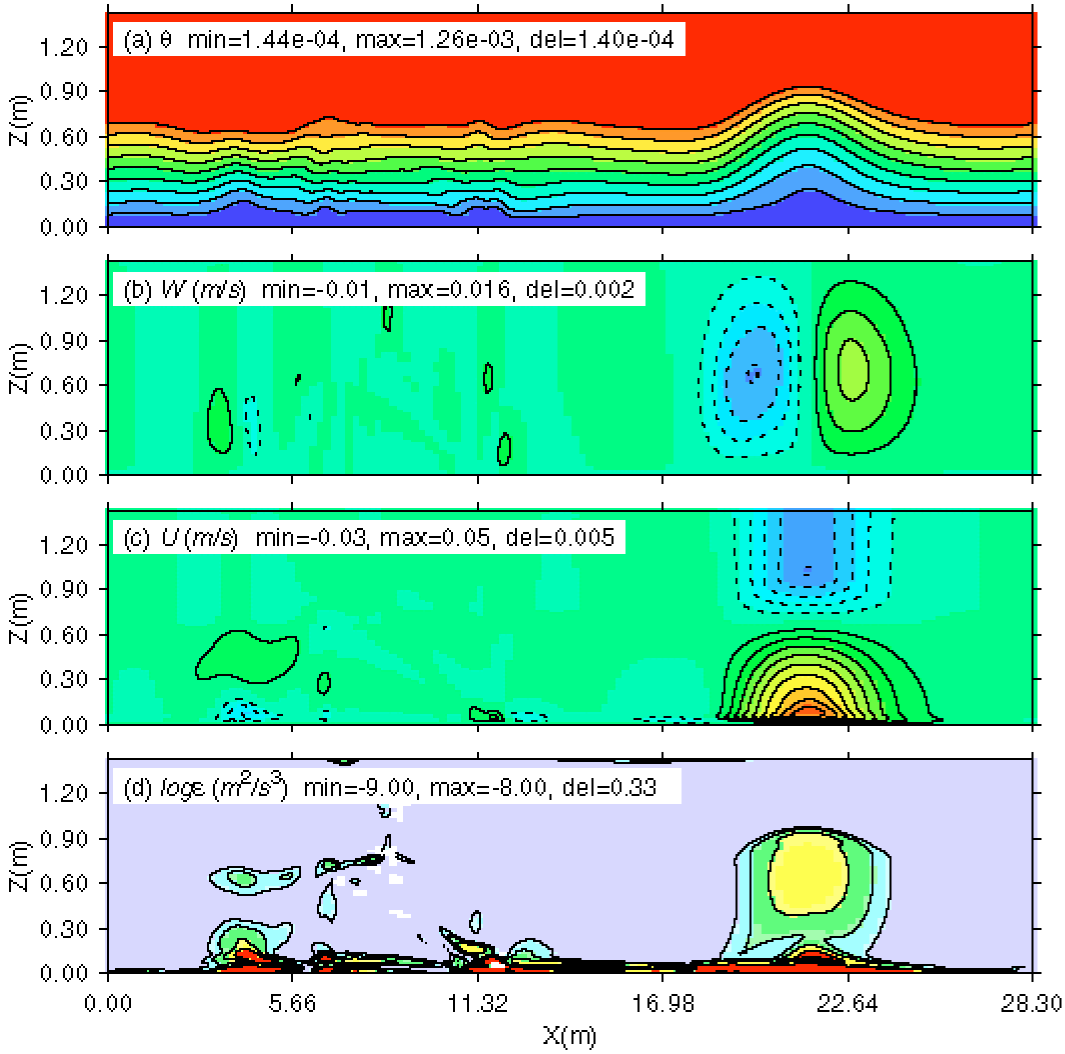

Figure 2: Cross-section of a simulated solitary wave, showing temperature, vertical and horizontal velocity components and TKE dissipation rate.

IMPACT / APPLICATIONS

TRANSITIONS

I am in regular communication with M. Levine, T. Boyd and J. Barth, who are analyzing observational data from CMO, and with K. O'Driscoll, who is conducting analytical studies using a modified KdV equation. D. Bogucki is studying soliton dynamics on a more fundamental level, using a combination of DNS and analytical approaches. Dr. Bogucki's project and my own are closely complementary; it is possible that we will collaborate on future extensions of this research.

REFERENCES

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